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THE EFFECT OF TEMPERATURE CYCLING ON THE PHYSICAL PROPERTIES OF 75S-T6 ALUMINUM ALLOY SHEET METAL

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THE EFFECT OF TEMPERATURE CYCLING ON THE PHYSICAL PROPERTIES OF 75S-T6 ALUMINUM ALLOY SHEET METAL

Thesis by

Lt. W. P. Robinson, USN

In Partial Fulfillment of the Requirements
For the Degree of
Aeronautical Engineer

California Institute of Technology
Pasadena, California
1953

Thesis
R643

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20547

SUMMARY

This thesis is a report on the results of an experimental investigation into the effects of cyclic heating and cooling prior to testing on the tensile and creep properties of aluminum alloy 75S-T6 Alclad sheet. A similar investigation concerning magnesium alloy sheet is described by J. N. Lindsley in Reference 1.

Specimens of 75S-T6 Alclad sheet were cyclically heated in an electric oven to either 250°F or 550°F and cooled to 100°F. All specimens remained at elevated temperature an aggregate of 60 minutes, with the number of cycles during the hour varying from one to twenty. Tensile tests and short time creep tests (6 minutes) were performed at room temperature and at the temperature of heat treatment.

It was found that at room and elevated temperatures the modulus of elasticity and 0.2 per cent yield strength were essentially independent of the number of heating cycles, as were the minimum creep rates at room temperature and at 250°F. The minimum creep rate at 550°F increased exponentially with the number of cycles. Specimens heat treated at 550°F and creep tested at room temperature showed practically no creep at any stress in six minutes.

Without regard to the cycling, the 0.2 per cent yield strength at room temperature was relatively unaffected by the 250°F heat treatment, but was reduced by a factor of four or more by the 550°F heat treatment. The modulus of elasticity at room temperature after either heat treatment remained very near the value for the untreated material at room temperature. Values from test conducted at elevated temperatures have been given in reports of previous investigations.(6)

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I. INTRODUCTION

The high speeds of present aircraft are introducing serious problems concerning the temperature effects on the skin and structural components of these aircraft. At sea level, the temperature rise in degrees Fahrenheit is of the order of 100 x $(\text{Velocity}/763)^2$, where the velocity is in miles per hour. Already, aircraft have been built of stainless steel and Monel metal to avoid these adverse effects. Engineering departments of aircraft companies have imposed maximum temperature limits for the use of metals normally used for the skin and structural components. These limits are conservative, of necessity, because of the lack of information on the extent of the changes which occur in the properties of metals both during and after exposure to elevated temperatures.

Repeated exposure to high temperatures might cause a slightly different change in properties, possibly as a function of the number of exposures, or as a function of the time of exposure. The purpose of this investigation therefore was to attempt to clarify the effect of repeated heating and cooling, as might be encountered during alternately high and low speed flight, on the tensile and creep properties of usual aircraft metals. The investigation was divided into two parts; one concerning magnesium alloy sheet;(1) and one concerning aluminum alloy sheet. This paper reports the results of the tests conducted on the aluminum alloy sheet material.

Relatively little research similar to that described in this report and in Reference 1 has been done. Several references are available for tests at temperatures on untreated material. References 2, 3, 4, and 5 describe short-time creep properties at elevated temperatures.

Reference 6 describes the tensile, compressive, bearing, and shear properties of 75S-T6 (Alclad) aluminum sheet (and other materials) tested at temperatures ranging from 300°F to 600°F, after heat treating at the same temperatures for periods ranging from one-half to 1000 hours. Most properties of the 75S-T6 sheet are greatly reduced at 400°F, and the properties at 300°F show marked reductions for exposure times above 100 hours.

This investigation was conducted at the California Institute of Technology, Guggenheim Aeronautical Laboratory, Pasadena, California, during the period from September, 1952 to May, 1953, under the supervision of Dr. E. E. Sechler and in cooperation with J. N. Lindsley, Lt. USN.

II. EQUIPMENT

Three furnaces, with frames for conducting creep tests, were available from a previous investigation. Their construction is described in References 2, 3, and 4. One of these furnaces was modified to facilitate the cyclic heating and cooling of specimens. It was not necessary to modify the others for this investigation.

The furnace which was to be used for preparing the specimens was modified by increasing the opening at the bottom to a three-inch diameter, and the opening at the top was sealed with insulating material. A hole slightly larger than three inches in diameter was made in the upper plate of one of the stands. The modified furnace was placed over this hole, and a pneumatic cylinder weith a 20-inch stroke was mounted below. A light supporting structure, capable of holding four specimens, was mounted on the end of the cylinder. A tandem recycling timer was used to control the position of the cylinder. A General Electric time switch was used to shut off the controlling timer and end the cycling. The components are shown in Figures 1 and 2.

The maximum gradient over the specimen length, after reaching constant temperature, was two degrees Fahrenheit, both at 250° and 550°F.

A three-thousand-pound compound lever tensile machine was modified slightly allowing one of the furnaces to be supported within it, to conduct tensile tests at elevated temperatures. Figure 3 shows the testing machine with the furnace in place. The remaining furnace was used in conjunction with one of the creep testing frames. No

modifications were necessary. Figure 4 shows the creep testing set up. A close up of the specimen is shown in Figure 5. Oven temperatures were controlled with automatic Sym-Ply-Trol controlling pyrometers.

Elongations were measured with a Huggenberger extensometer for the room temperature tensile tests. Elongations for all other tests were measured by means of two portions of a machinist's scale, mounted on the specimen, and viewed through two eight-power telescopes. The scales were graduated in hundredths of an inch, and interpolations were made to the nearest tenth of a graduation. One of the scales is shown in Figure 6. The mounted telescopes are visible in Figure 3.

Jaws for gripping the specimens were constructed of stainless steel. The same pair of jaws was used for both tensile and creep tests, and one pair is illustrated in Figure 7.

III. TEST SPECIMENS

The test specimens were manufactured from 75S-T6 rolled Alclad sheet, with a nominal thickness of 0.102 inches. The grain due to rolling lay along the longer axis of the specimen. The dimensions of the specimen are given in Figure 8 and are similar to those given in Reference 7. All specimens were painted black to reduce the transient heating and cooling time. The properties as received are itemized in Table I, and shown in Figures 13, 15, 16, 17, 18, and 19.

IV. PROCEDURES

A. Preparation of the Specimens

The treating furnace was brought up to temperature and allowed to remain there for at least one hour, with the supporting structure inside the furnace. The supporting structure was then lowered, four specimens mounted in it, and the automatic cycling was begun, so that the specimens immediately entered the furnace. Regardless of the number of heating and cooling cycles, the total time at temperature was one hour. This did not include the transient heating time, but time was begun when the specimens were within 2 percent of the scheduled temperature.

After the specimens had remained at the scheduled temperature for the appropriate number of minutes (three minutes for the three-minute twenty-cycle group) they were lowered from the furnace automatically by means of the pneumatic cylinder, and cooled to 100°F. They re-entered the furnace, and the next cycle began.

The treating temperatures were 250° and 550°F. The treating and testing schedules are given in Table II. Plots of the transient heating and cooling time-temperature curves are given in Figures 9 and 10. The treated specimens were allowed to age at room temperature for several days prior to testing.

B. Creep Testing

The jaws, with a specimen mounted in them, were installed in the testing apparatus. The machinist's scales were attached, and

adjusted so that they were easily visible through the telescopes, and the gage length was recorded. A preload was applied, well within the elastic limit, to allow the jaws to set into the surface. The preload was removed, and the full load was placed on the loading pan, which was supported by a mechanical jack. When the recorder was ready, the jack was lowered until the loading pan was no longer supported by it. Zero time was declared at the instant the pan was free, and readings were taken at fifteen-second intervals for six minutes. The time required for lowering the jack until it no longer supported the pan varied between five and twenty seconds, depending upon the weight and the original deflection.

For the elevated temperature creep tests the oven was preheated for approximately one hour, or was already hot from a previous test, and the specimen was always installed into hot jaws. After mounting a control thermocouple and a monitoring thermocouple to the center of the specimen, the oven heat was turned on, and the specimen was brought up to temperature. Approximately nineteen minutes were required to reach the 550°F testing temperature, and the gradient along the gage line of the specimen was ten degrees. The time to reach the 250°F testing temperature was four minutes, and the gradient was six degrees. It was not necessary to apply a setting load at the higher temperatures. The remaining procedure was the same as for the room temperature tests.

The constant stress at which creep rates were measured was the same for each group of tests, and is given in Tables I and III. An attempt was made to use a stress which gave a determinable minimum creep rate in six minutes or less.

C. Tensile Testing

The procedure for installing the specimen in the jaws was the same as in the creep tests. A Huggenberger extensometer was used for the room temperature tests and readings were taken at specified loading intervals. A preloading was necessary to set the jaws in most cases.

Preparation for the elevated temperature tests was identical to that for the creep tests. Loading intervals depended upon the temperature, since the properties varied with the temperature, but at least twelve points were obtained for each test. Elongations were measured by means of the machinist's scales and the telescopes.

V. RESULTS AND DISCUSSION

The results are presented graphically in Figures 11 through 19 and itemized in Table III. Figures 11 and 12 show the yield strength, modulus of elasticity, and minimum creep per hour versus the number of cycles. Figures 13 through 19 show the various test results grouped according to the temperature of treatment and the temperature of testing.

As may be seen in Figure 11, the tensile properties at room temperature and at elevated temperature are essentially independent of the cycling. The yield strengths for the group treated at 250°F and tested at room temperature are not included, since the testing machine limit was reached before yields of 0.2 percent were obtained. The similarity of the curves as shown in Figure 13 indicate no appreciable variation with the number of cycles. The only adverse effect, as compared with the untreated specimen, is a slight lowering of the modulus of elasticity, from 9.8×10^6 psi to 9.5×10^6 psi.

It may be noted that the curves show two relatively straight portions, which is typical of Alclad material. The specimen treated for 12 five-minute cycles shows this to a greater degree than the others, but this is not attributed to the cyclic heating. None of the other groups of tests shows this effect, probably because the treatment, or temperature of testing, reduced the properties to values closer to those of the cladding material.

The room temperature tensile tests of the specimens treated at 550°F (Figure 14) show a marked reduction in yield stress, although the modulus of elasticity is only slightly affected.

All of the tensile tests at temperature show considerable scatter, obviously due to the method of measuring elongations. For the group tested at 250°F, two of the tests show an apparent shift in the straight portions of the curves. During one of these tests it was necessary to move the oven slightly to keep the scales in the field of view. This indicates the possibility that the scales tipped or slipped. Therefore the shifts are believed to be due to experimental errors.

It may be seen from Figure 15 that there is little difference between the treated and untreated specimens tested at 250°F, it may be concluded that previous exposure to 250°F has little adverse effect on the tensile properties in the normal working range of the material, either at room temperature, or at 250°F.

The tensile specimens tested at 550°F,(Figure 16) show a marked reduction in properties as compared with the specimens treated at 250°F. The treated specimens also show reduced properties as compared with the untreated specimen tested at 550°F, and a small gradual reduction in yield strength with an increase in the number of cycles. The advantage of the strength to weight ratio of this material becomes a disadvantage at 550°F, or after exposure to 550°F. Therefore it may be concluded that this material is unsatisfactory for use at 550°F, or for use after exposure to 550°F.

Considering the creep curves, the only group of tests showing a significant change with the number of cycles of heating was the one for the tests conducted at 550°F (Figure 17). It may be seen in Fig. 12 that the minimum creep rate doubled as the number of cycles increased from one to twenty. This was to be expected on the basis of the tensile

tests conducted at 550°F, since the 0.2 per cent yield strength decreased slightly with an increase in the number of cycles. It should be noted that the total time of exposure to heating is actually much greater for twenty cycles of heating, since the transient heating time must be included for each cycle.

The two groups treated at 250°F (and tested at 250°F and at room temperature - Figures 18 and 19) show relatively straight line variations of minimum creep rates with the number of cycles, with only slight increases in minimum creep rates as the number of cycles increases. The group tested at room temperature (Figure 19) has the minimum rates at the ends of the tests, which may not indicate the true minimums. In an attempt to rectify this situation, the stress was increased slightly, but failure occurred either before, or immediately after the full load was applied.

No data are included for the group treated at 550°F and tested for creep at room temperature. The maximum stress which the specimens would sustain was 38,000 psi, but no significant extensions could be perceived after the first minute. The extensions for the first minute were of the order of 0.001 inches for a three-inch gage length. It is estimated that the minimum creep rates were of the order of 0.001 inch per inch per hour.

The conclusions may be summarized as follows:

1. For the temperatures considered, tensile and creep properties are relatively independent of the number of cycles of heating, with the exception of creep tested at 550°F after heat treatment at 550°F.

2. One hour exposure to, or use at 250°F can be tolerated, provided that the working stresses are lowered about 10 per cent.

3. One hour exposure to 550°F reduces the room temperature yield strength to about 25 per cent of the value for untreated material, while the yield strength at 550°F (even for previously untreated material) is below 15 per cent of the room temperature value for untreated material.

VI. RECOMMENDATIONS

The following recommendations are proposed:

1. That investigations be conducted varying the time of exposure only, to determine the maximum time of exposure before which detrimental effects are insignificant.

2. That investigations similar to those described in this report be conducted at temperatures between 250° and 400°F to determine the maximum exposure temperature below which detrimental effects are insignificant.

3. That a more refined means of measuring extensions be considered, such as a cathetometer with two independent eyepieces connected by a dial gage.

4. That investigations be made to determine the effect of the rate of loading on creep.

5. That changes be made in the system to eliminate or greatly reduce the time of transient heating.

1. Lindsley, J. N.: "The Effect of Temperature Cycling on the Physical Properties of FS-1 Magnesium Alloy Sheet Metal", A.E. Thesis, California Institute of Technology, 1953.

2. Gaibler, R.: "Column Creep of 75S-T6 Aluminum Alloy", A.E. Thesis, California Institute of Technology, 1952.

3. Thatcher, R. C.: "Short Time Compressive Creep in 75S-T6 and 25S-T6 Aluminum Alloy Short Columns", A.E. Thesis, California Institute of Technology, 1952.

4. Kauffman, R. J.: "An Investigation of Creep in Light Metal Alloys", A.E. Thesis, California Institute of Technology, 1952.

5. Van Echo, J. A., Page, L. C., Simmons, W. F., Cross, H. C.: "Short Time Cree Properties of Structural Sheet Materials for Aircraft and Missiles", Air Force Technical Report 6731, Part I, Wright Air Development Center, August, 1952.

6. Doerr, D. D.: "Determination of Physical Properties of Nonferrous Structural Sheet Materials at Elevated Temperatures", Air Force Technical Report No. 6517, Part I, Wright Air Development Center, December, 1951.

7. Eshbach, O. W.: "Handbook of Engineering Fundamentals", John Wiley & Sons, Inc., New York, 1947.

TABLE II

PREPARATION AND TESTING

Preparation		Testing	
Heating Cycles	Minutes/Cycle at Temp.	Tensile	Creep
1	60	Room Temp.	Room Temp.
		Temp. of Preparation	Temp. of Preparation
5	12	Room Temp.	Room Temp.
		Temp. of Preparation	Temp. of Preparation
12	5	Room Temp.	Room Temp.
		Temp. of Preparation	Temp. of Preparation
20	3	Room Temp.	Room Temp.
		Temp. of Preparation	Temp. of Preparation

Preparation temperatures were 250° and 550°F.

TABLE III

MECHANICAL PROPERTIES VERSUS NUMBER OF CYCLES

A. Modulus of Elasticity in Psi x 10^6

	Tested at Room Temperature			
Heating Cycles	Treated at 250°F	Treated at 550°F	Treated and Tested at 250°F	Treated and Tested at 550°F
1	9.55	9.25	8.85	5.7
5	9.74	9.25	8.85	5.8
12	9.50	9.25	8.85	5.7
20	9.45	9.62	8.9	5.8

B. 0.2°/o Yield Strength in Psi

1	Not Observed	19,700	60,400	9,650
5		19,500	60,400	9,830
12		18,200	60,200	9,100
20		18,100	60,300	8,600

C. Minimum Creep Rate in in./in./hr. (at stresses indicated below each column)

1	0.019	Not Observable (all estimated at 0.001)	0.25	0.54
5	0.013		0.30	0.54
12	0.040		0.27	0.62
20	0.038		0.24/0.35	1.05/1.17
Stress	74,300 psi		60,000 psi	10,000 psi

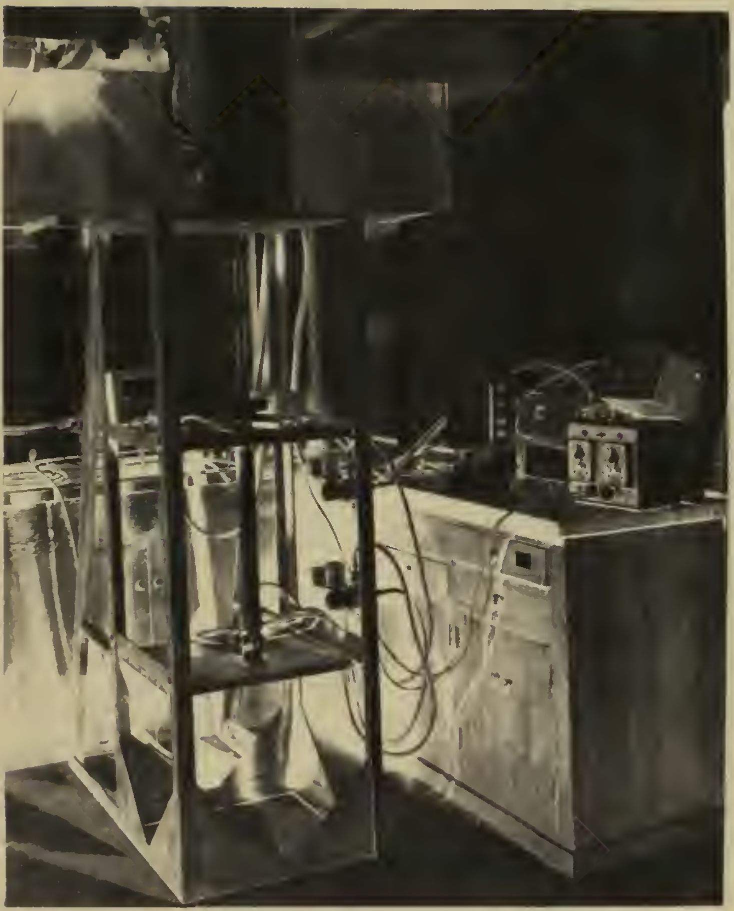


Figure 1 Heat Treating Furnace and Controlling Equipment

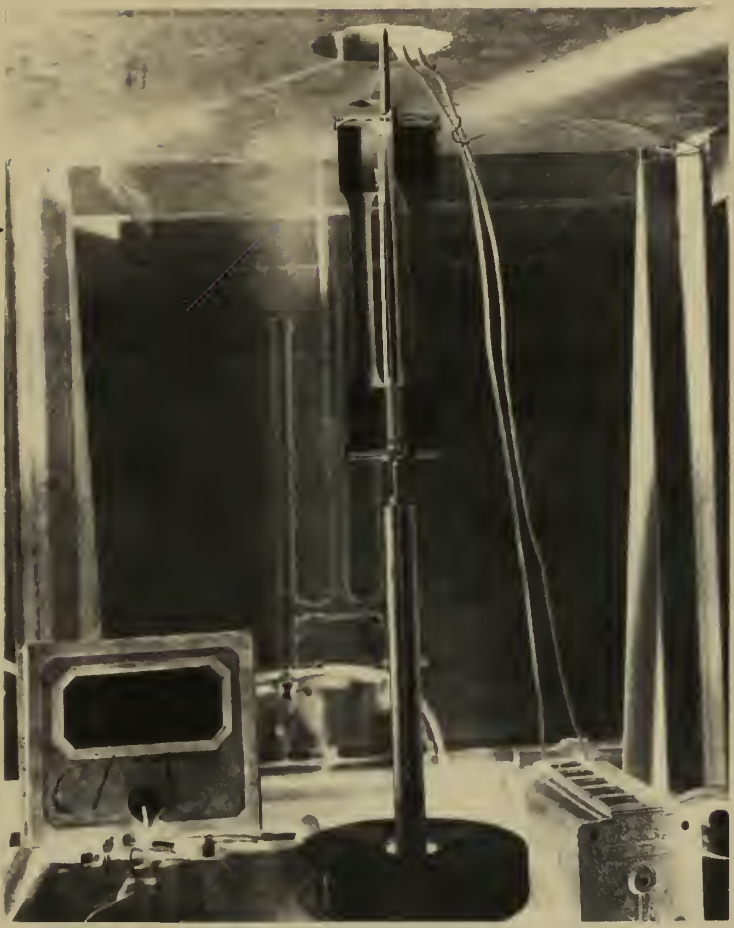


Figure 2   Supporting Structure with Specimens in Place

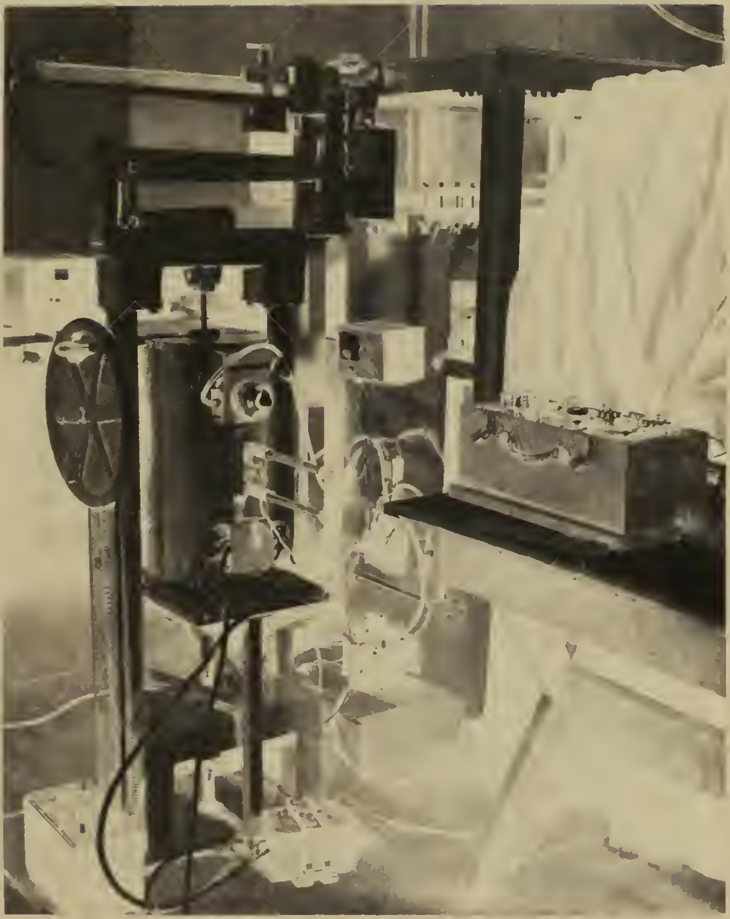


Figure 3 Tensile Machine with Oven in Position

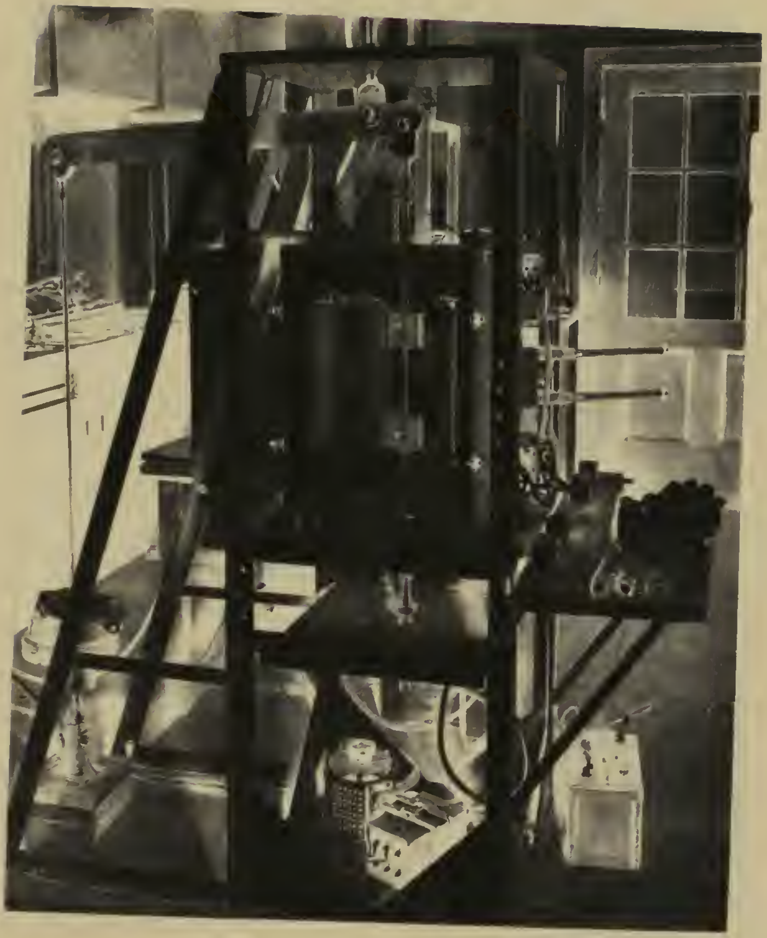


Figure 4 Creep Testing Equipment

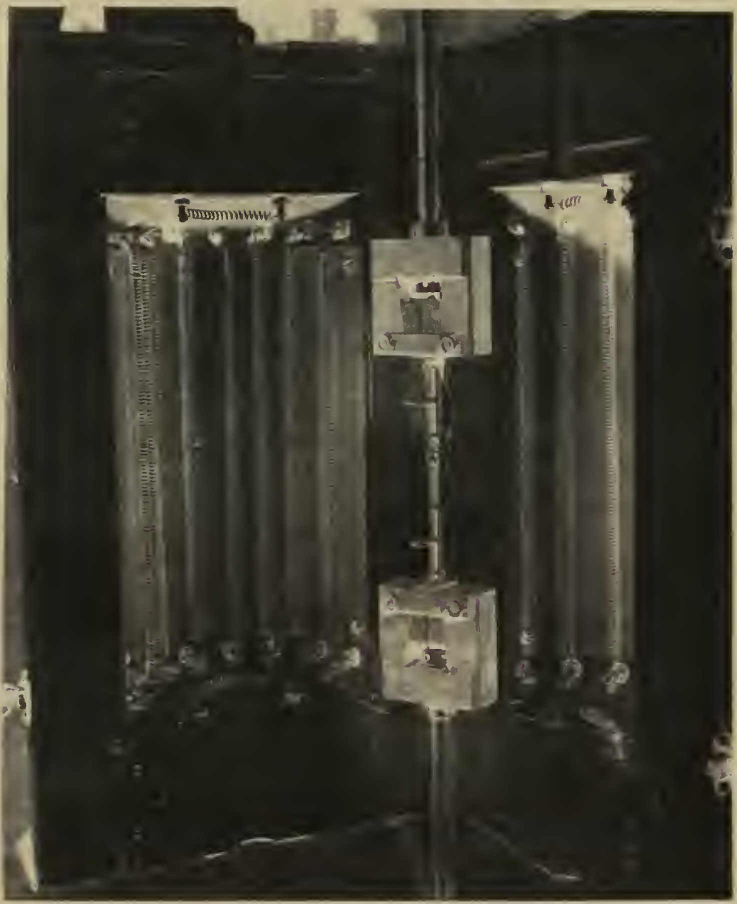


Figure 5 Close Up of Specimen Ready for Testing

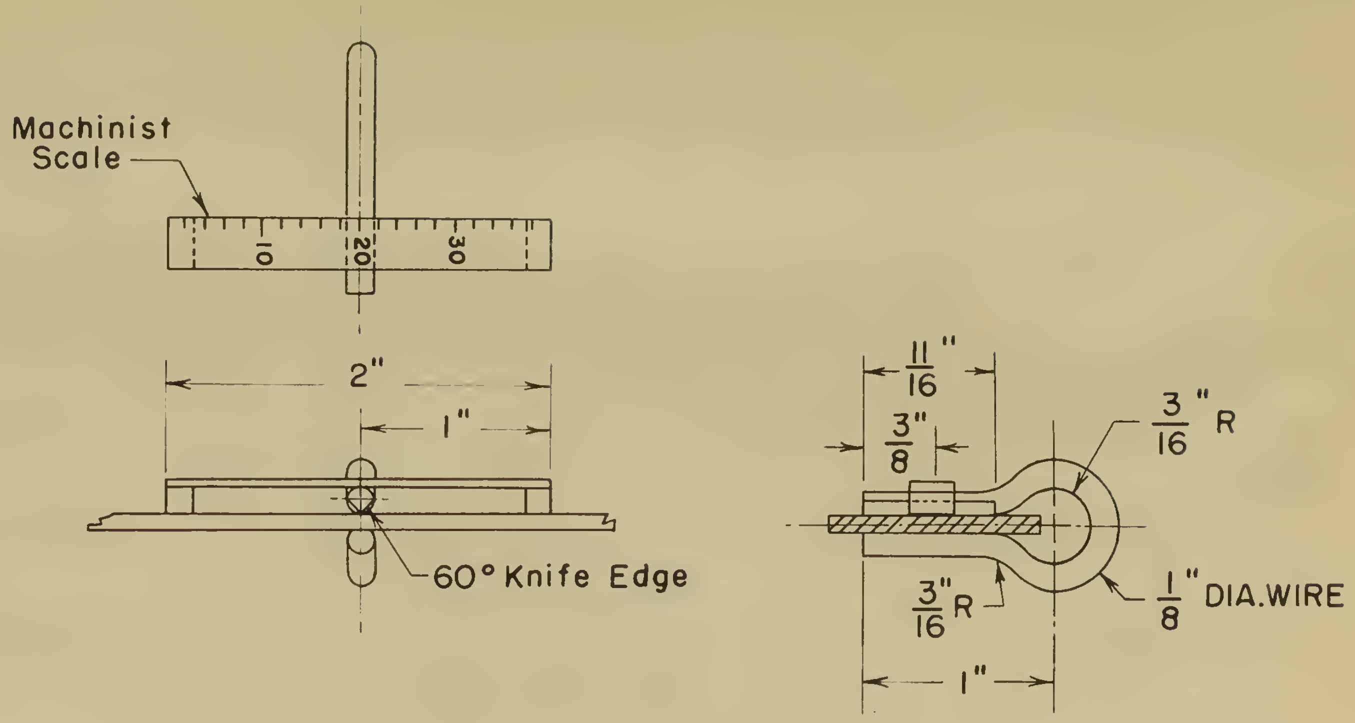
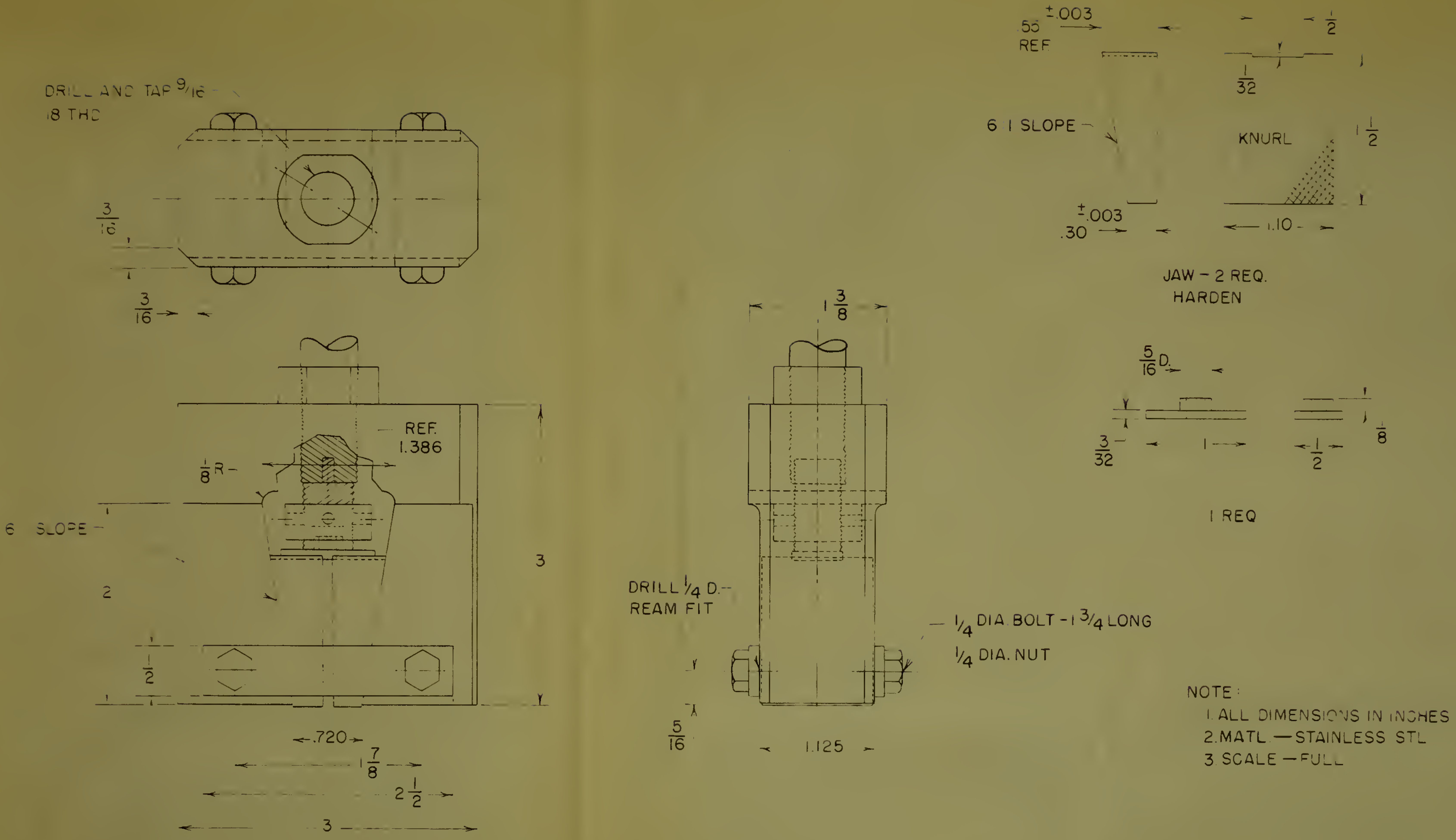

Machinist
Scale
10
20
30
2"
1"
60° Knife Edge
11/16"
3/8"
3/16" R
3/16" R
1/8" DIA. WIRE
1"

FIG. 6 — SPECIMEN SCALE CLIP


DRILL AND TAP 9/16 - 18 THD
3/16
3/16
1/8 R
REF. 1.386
6 : 1 SLOPE
2
3
1/2
.720
1 7/8
2 1/2
3
1 3/8
DRILL 1/4 D. REAM FIT
1/4 DIA. BOLT - 1 3/4 LONG
1/4 DIA. NUT
5/16
1.125
.55 ±.003 REF
1/2
1/32
6 : 1 SLOPE
KNURL
1 1/2
.30 ±.003
1.10
JAW - 2 REQ.
HARDEN
5/16 D.
3/32
1
1/2
1/8
1 REQ

NOTE:
1. ALL DIMENSIONS IN INCHES
2. MATL. — STAINLESS STL.
3. SCALE — FULL

FIG. 7 — TENSILE TEST GRIPS

DRILL
REAM
$\frac{5}{16}$

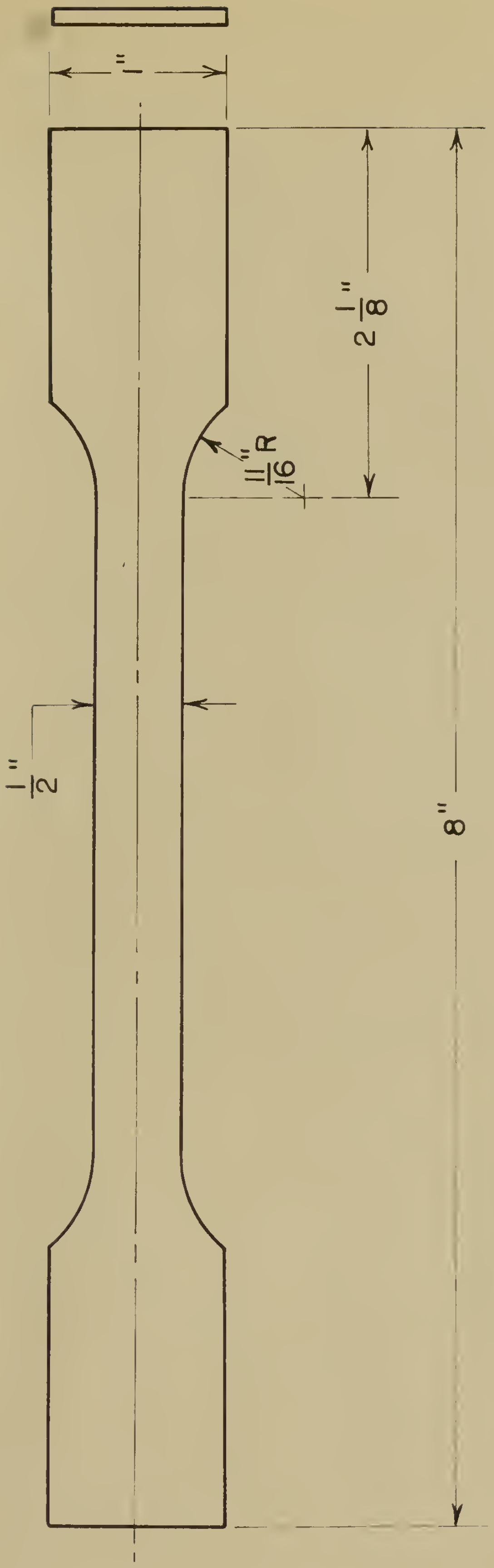

1"
$2\frac{1}{8}$"
$\frac{11}{16}$" R
$\frac{1}{2}$"
8"

FIG. 8 — TEST SPECIMEN

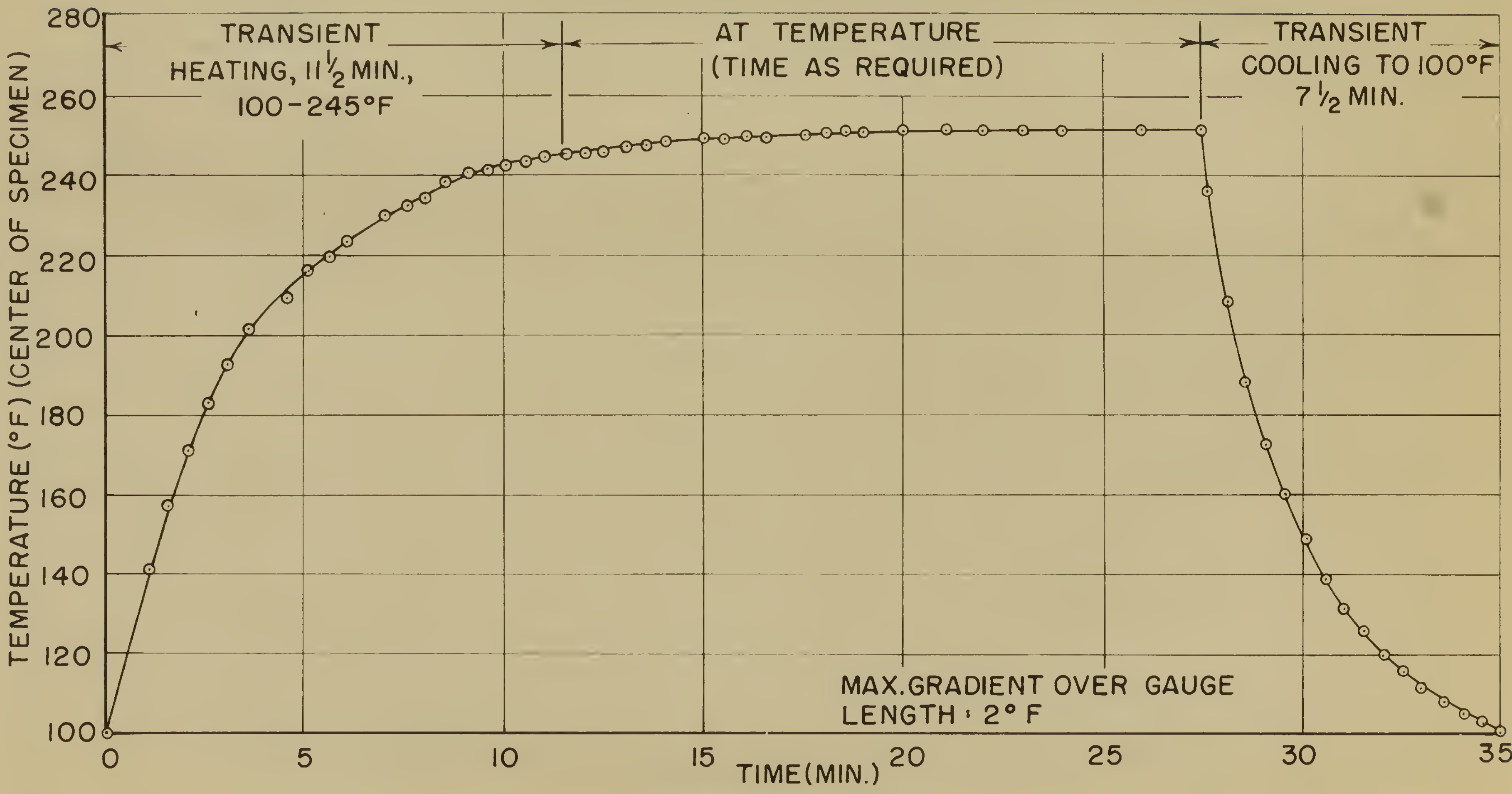


FIG. 9-TEST SPECIMEN HEAT TREAT CYCLE (250°)

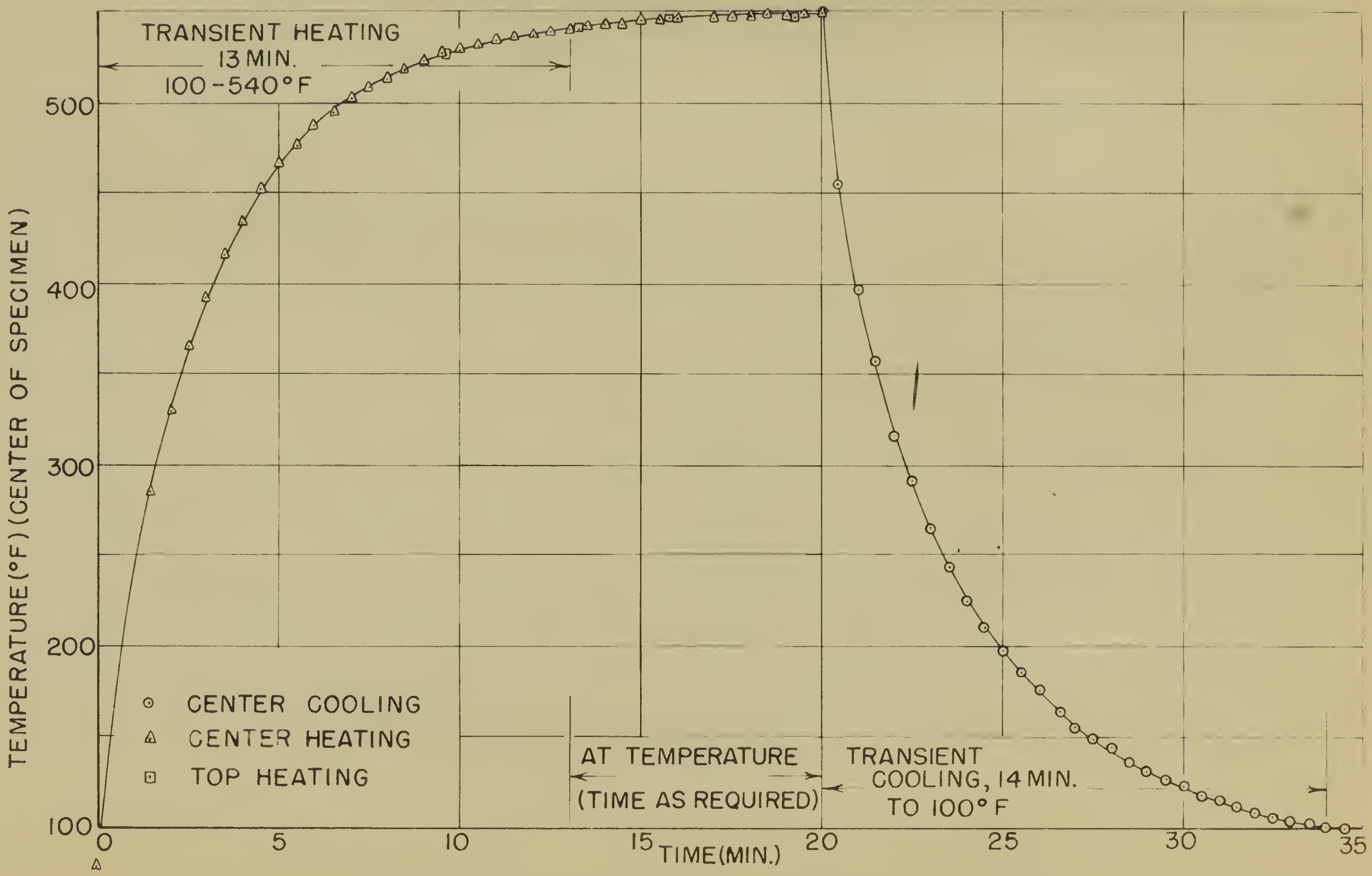


FIG. 10 - TEST SPECIMEN HEAT TREAT CYCLE (550°)

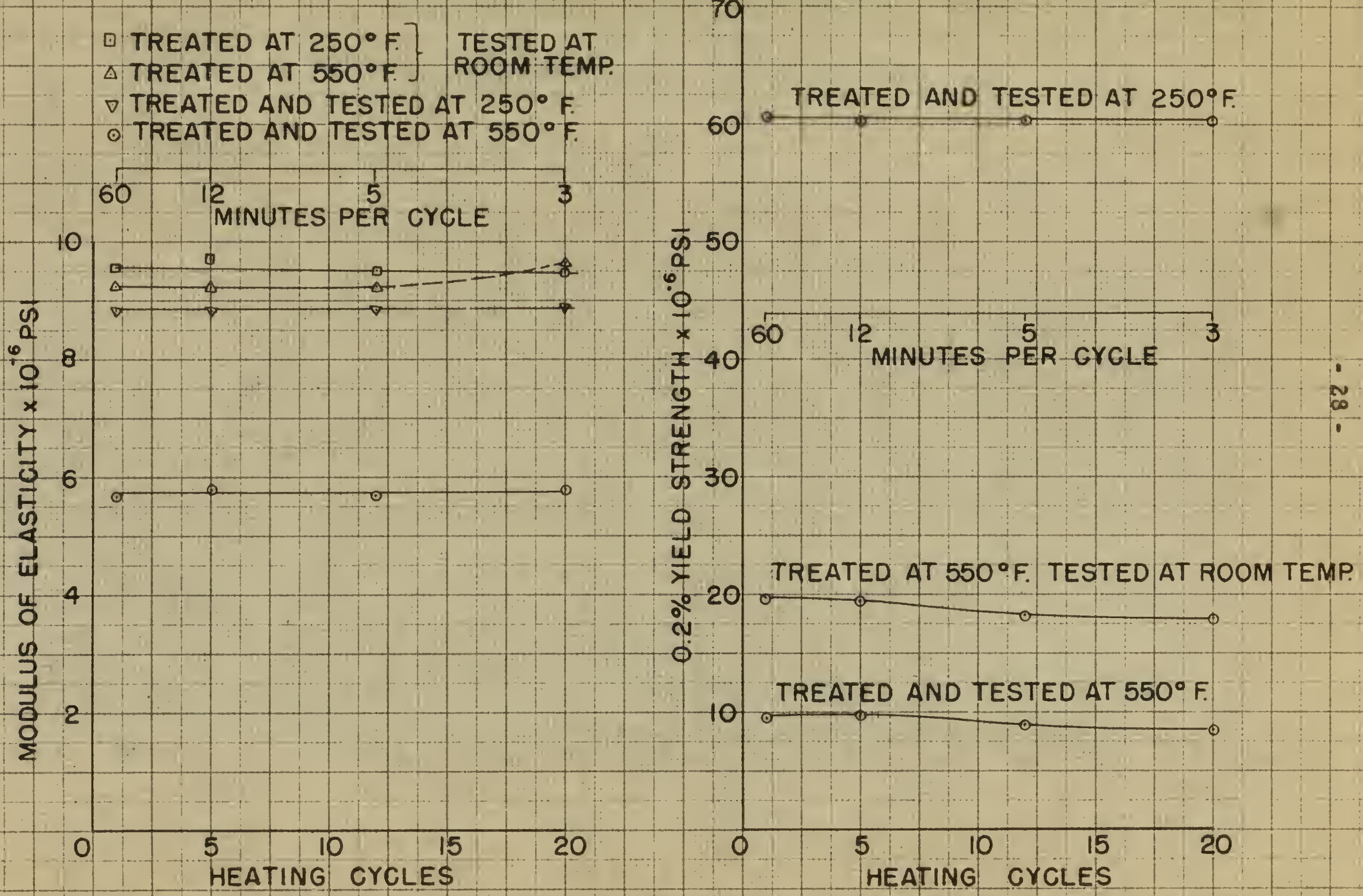


FIG. II - MODULUS OF ELASTICITY AND YIELD STRENGTH vs NUMBER OF HEATING CYCLES

NOTE:
SPECIMENS TREATED AT 550° F. AND TESTED AT ROOM TEMP. SHOWED NO OBSERVABLE CREEP IN 6 MINUTES.

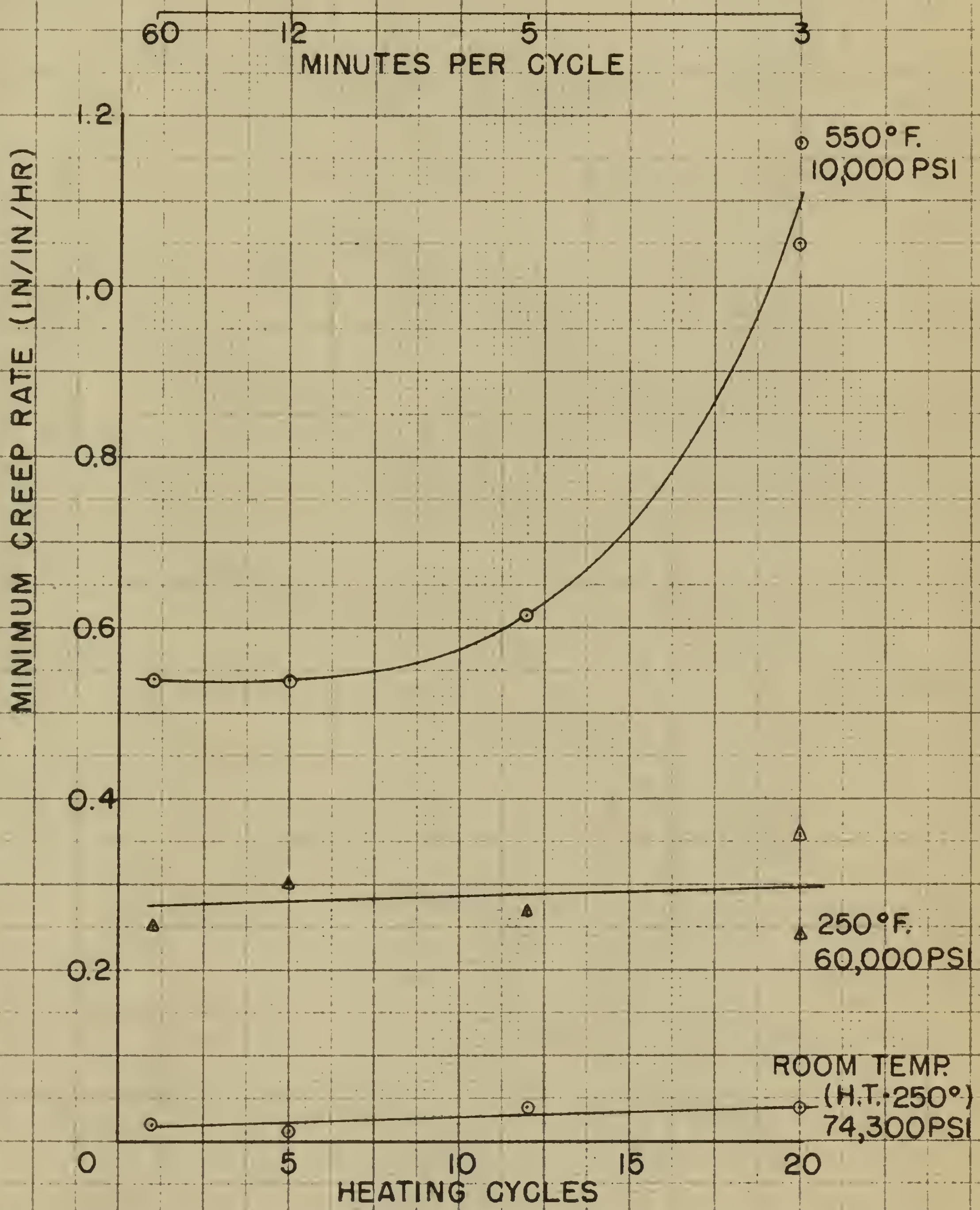
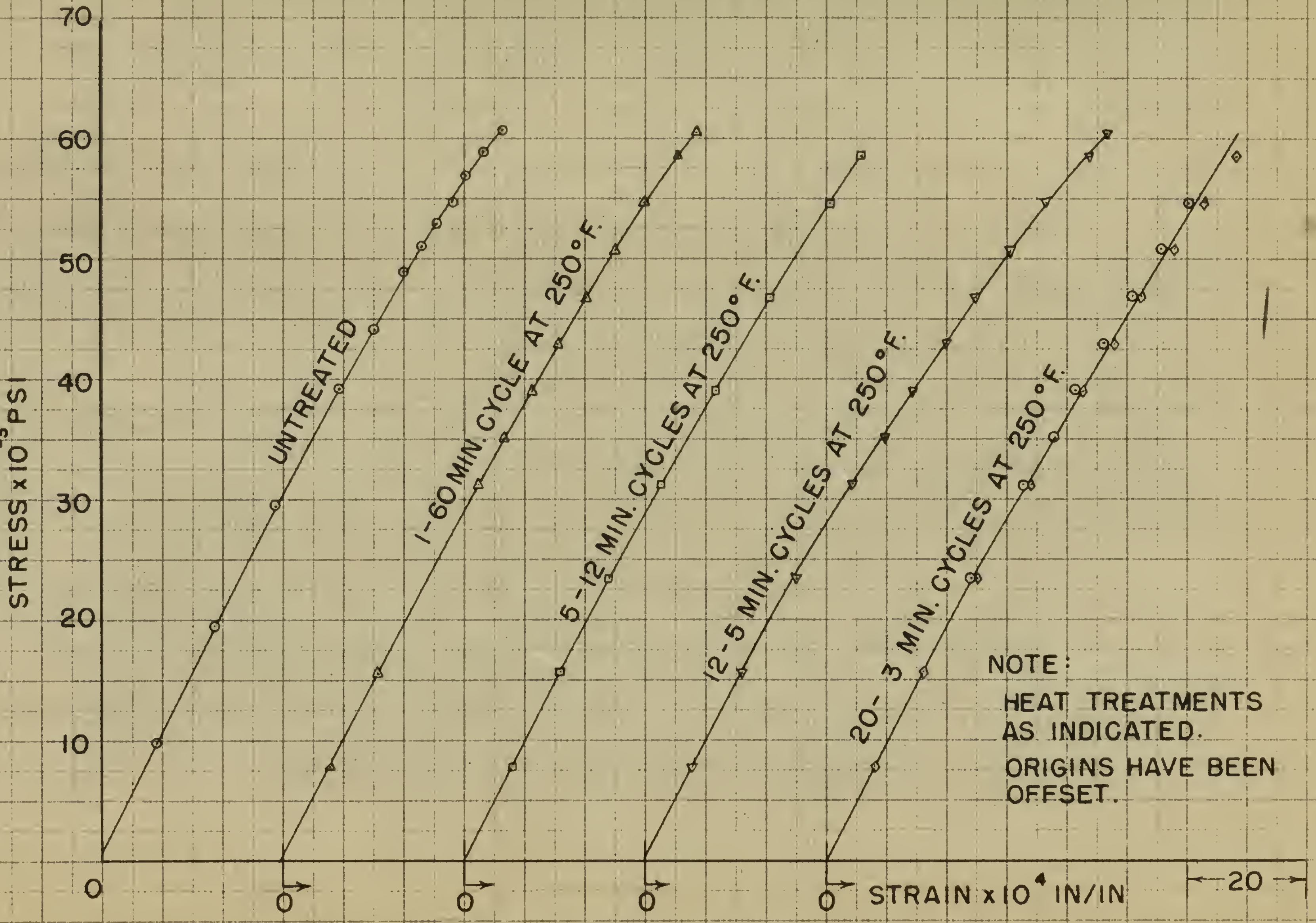


FIG.12-MINIMUM CREEP RATE vs NUMBER OF HEATING CYCLES



NOTE:
HEAT TREATMENTS AS INDICATED.
ORIGINS HAVE BEEN OFFSET.

FIG.13-STRESS-STRAIN TESTED AT ROOM TEMP.

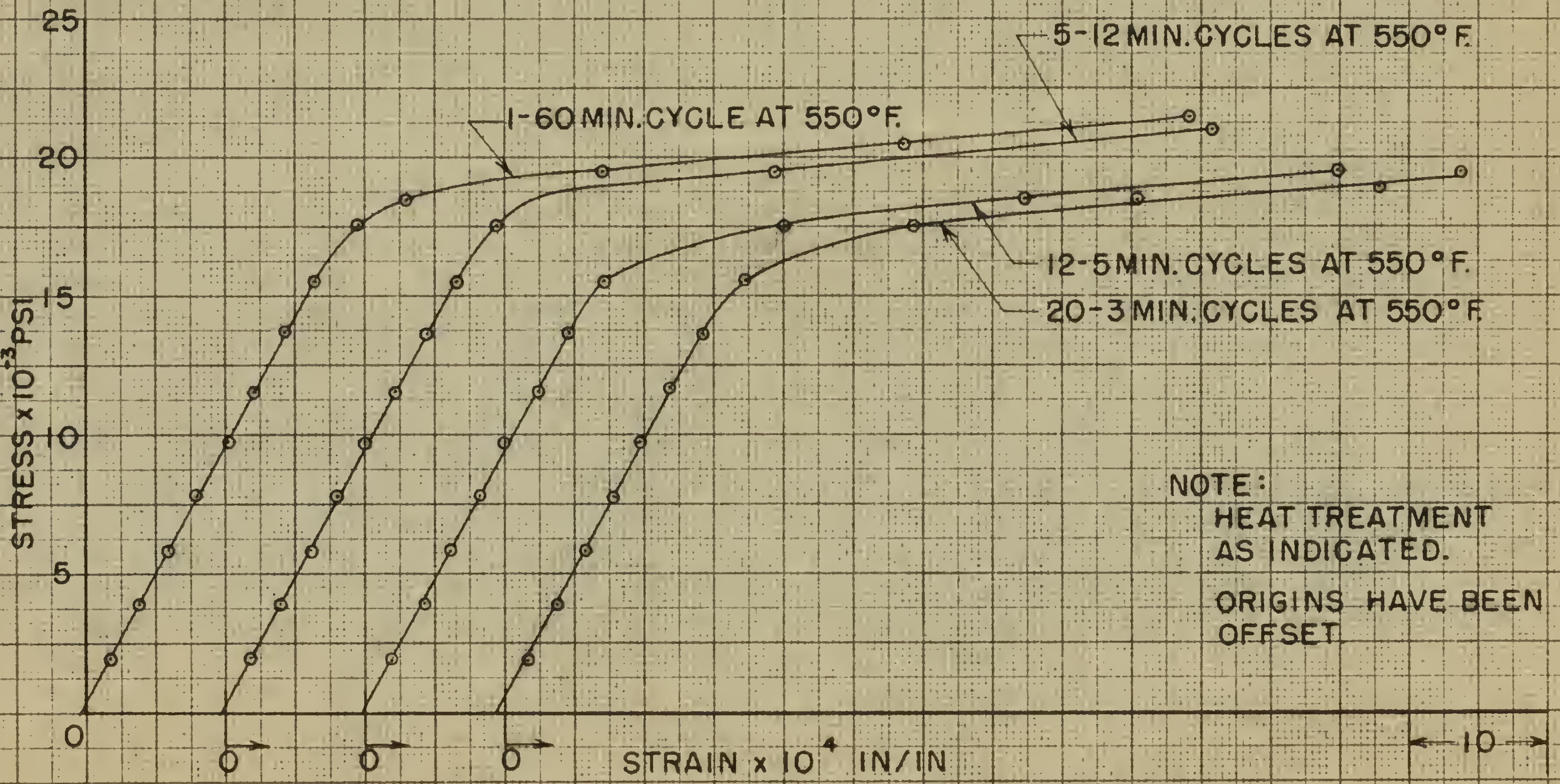


FIG. 14 - STRESS-STRAIN TESTED AT ROOM TEMP.

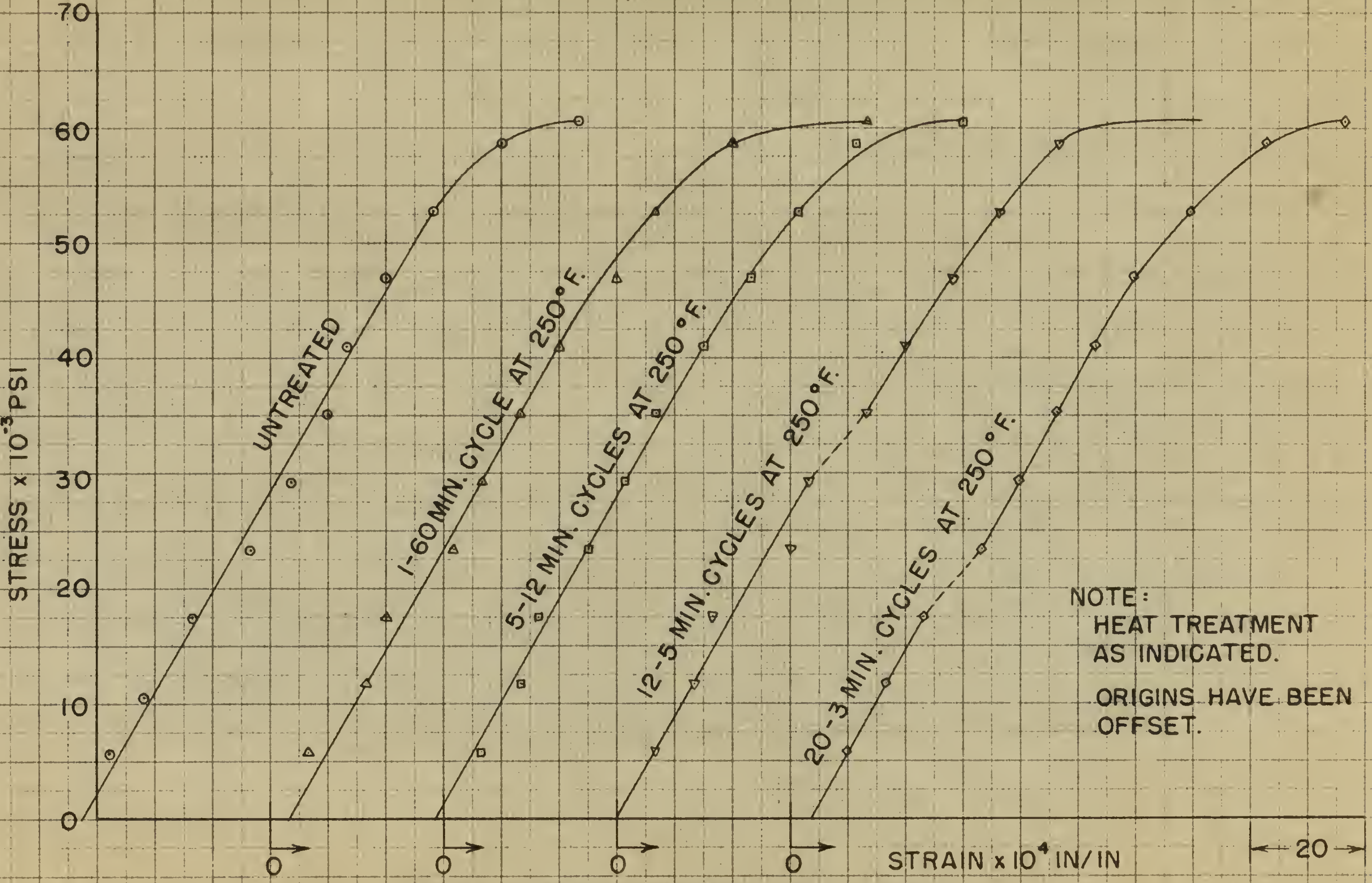


FIG. 15 - STRESS-STRAIN TESTED AT 250° F.

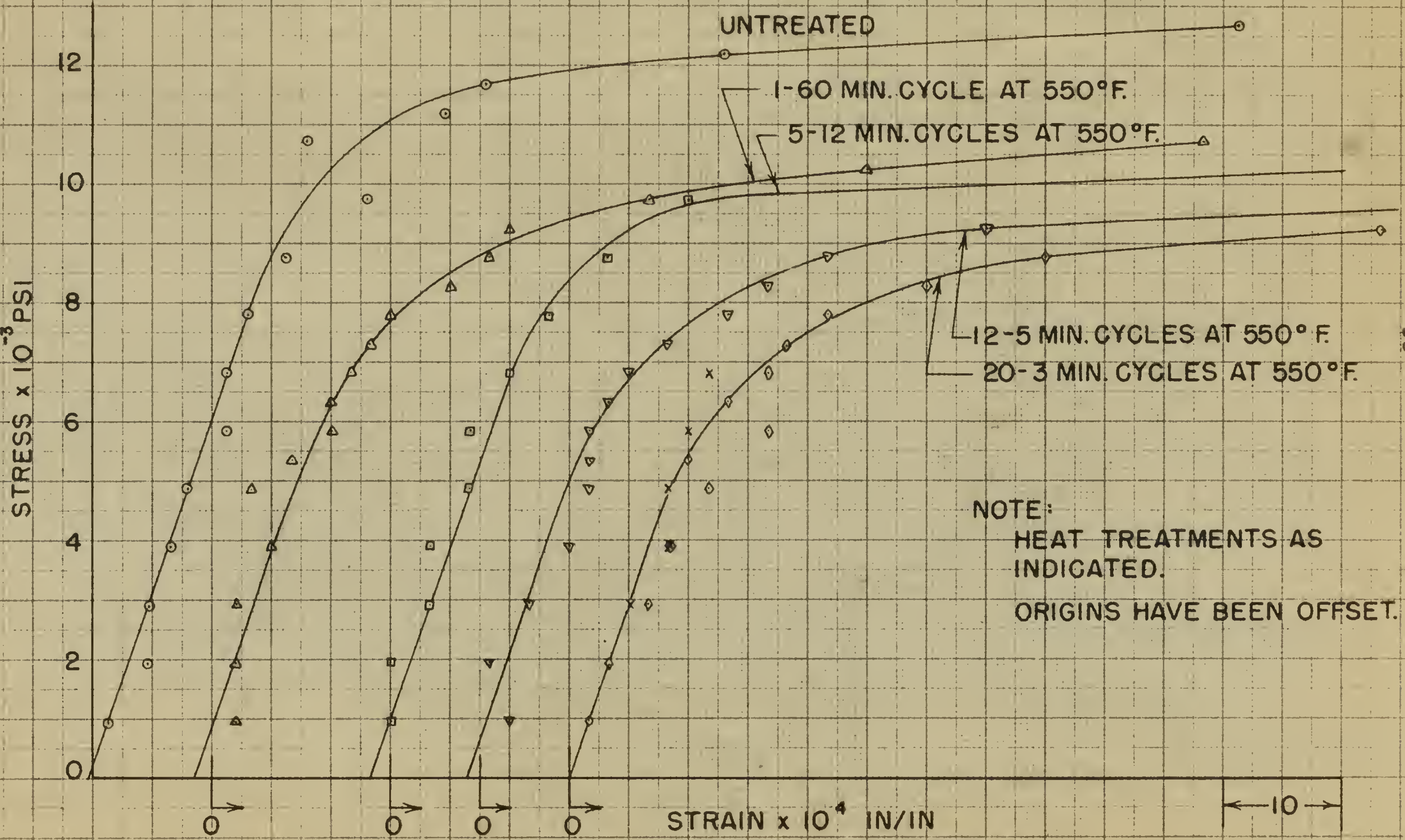
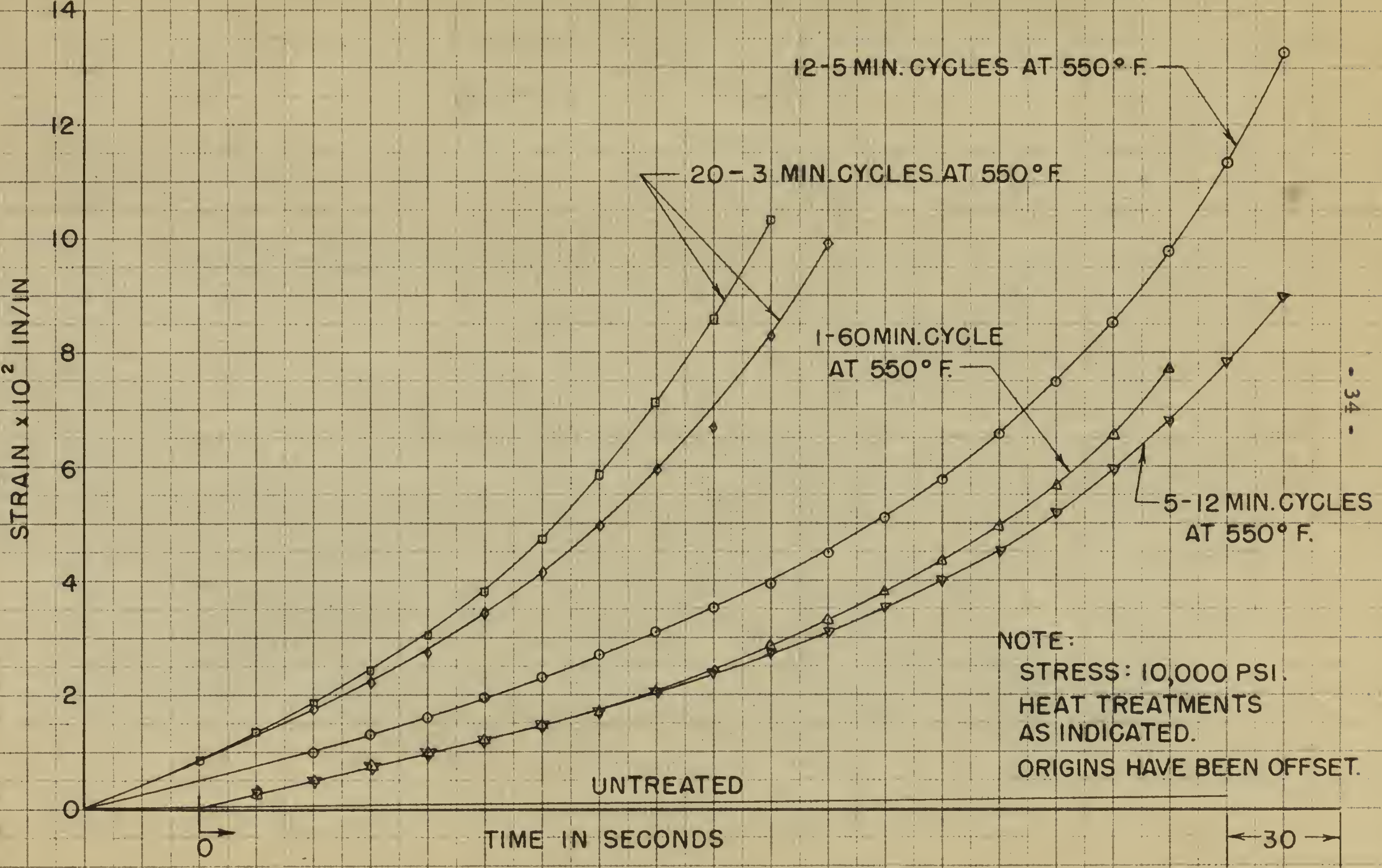
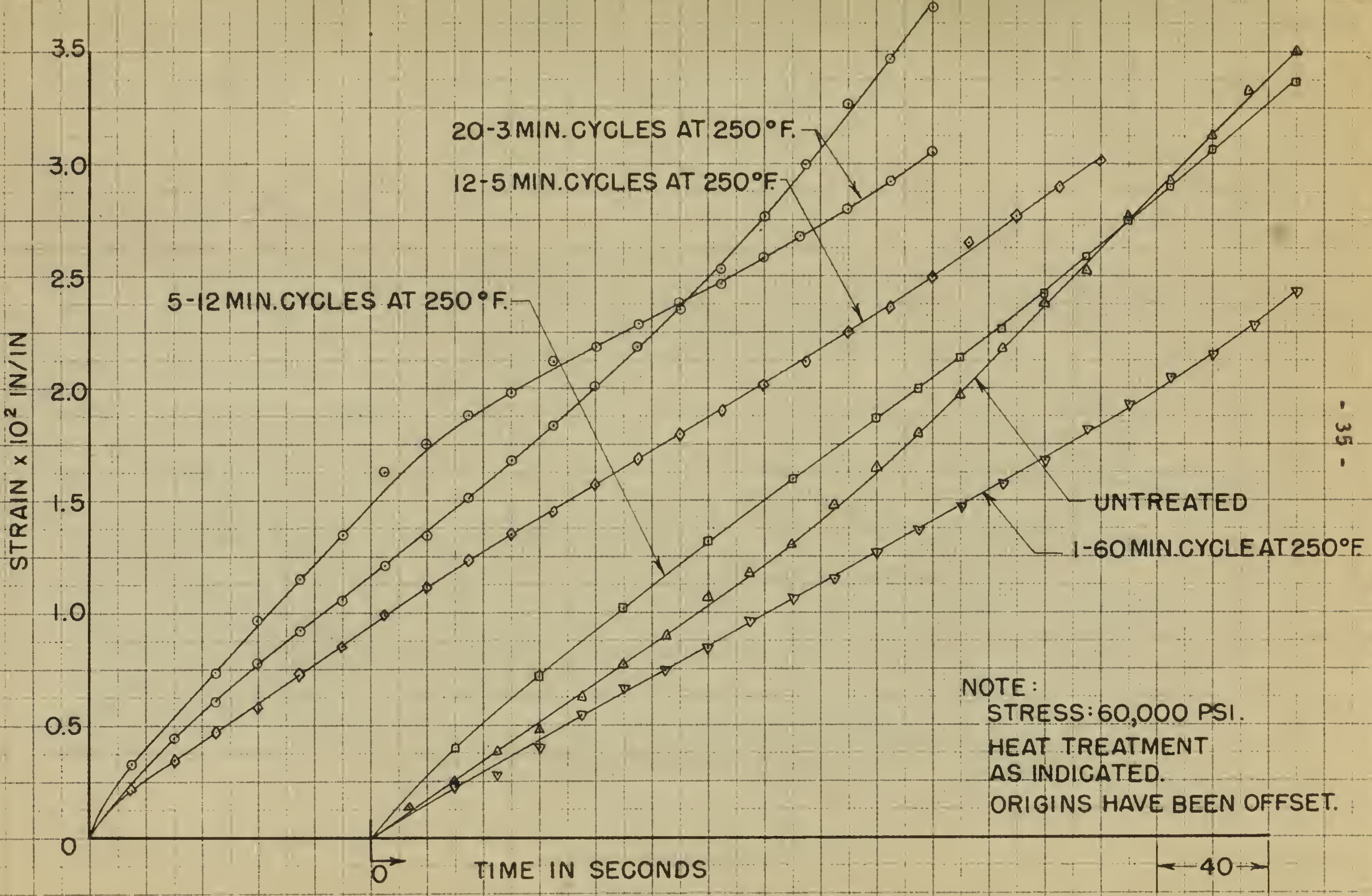


FIG. 16 — STRESS-STRAIN TESTED AT 550° F.



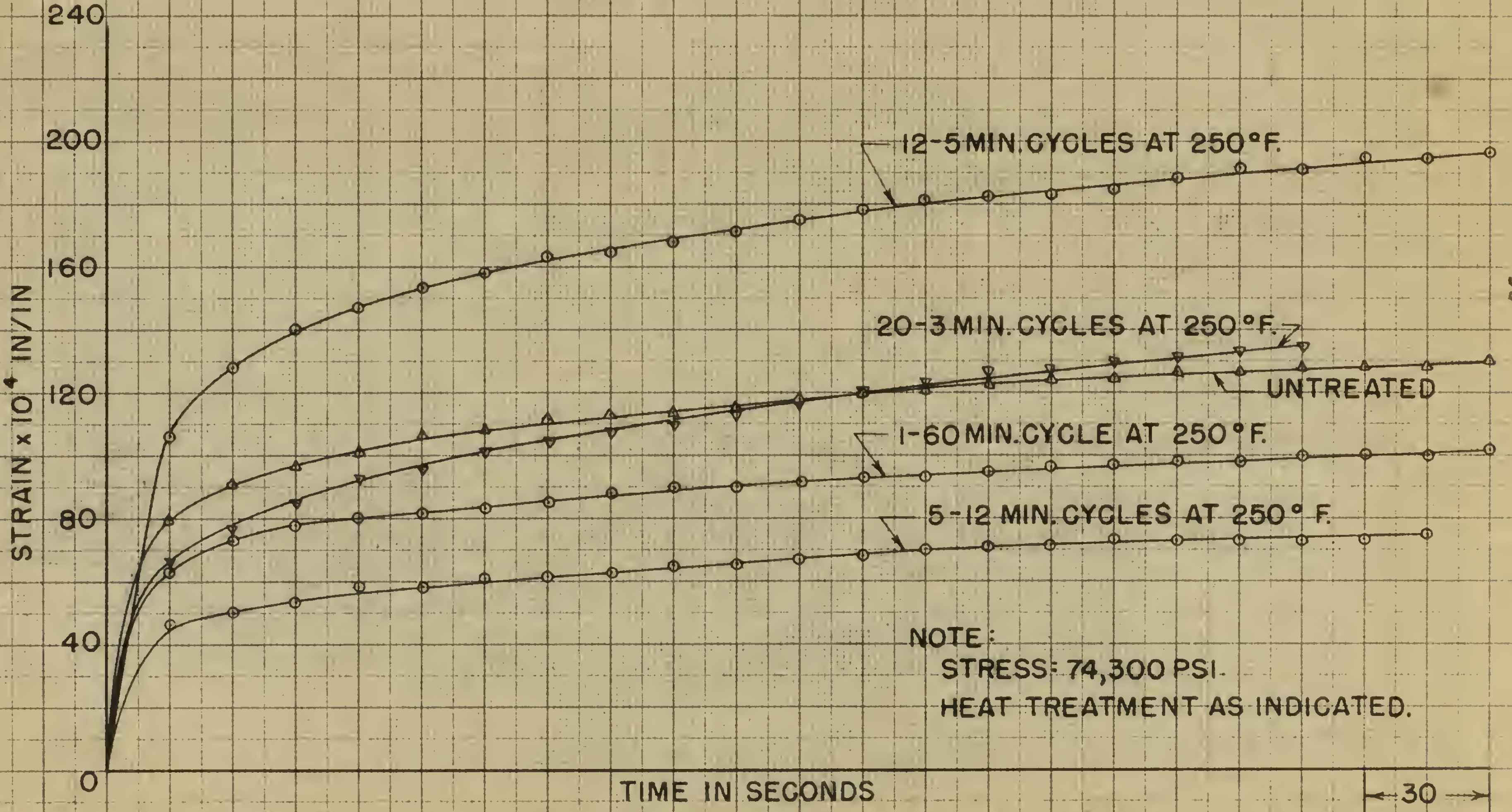
NOTE:
STRESS: 10,000 PSI.
HEAT TREATMENTS
AS INDICATED.
ORIGINS HAVE BEEN OFFSET.

FIG. 17 - CREEP TESTED AT 550° F.



NOTE:
STRESS: 60,000 PSI.
HEAT TREATMENT
AS INDICATED.
ORIGINS HAVE BEEN OFFSET.

FIG. 18 – CREEP TESTED AT 250° F.



NOTE:
STRESS: 74,300 PSI.
HEAT TREATMENT AS INDICATED.

FIG. 19 - CREEP TESTED AT ROOM TEMPERATURE

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